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The financial crisis and the dynamics of the money market rates

Nicole Hasler*

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Abstract

This paper contributes to the ongoing debate about the changing dynamics in the money market rates after 2007. It aims to analyse the interest rate channel of monetary policy transmission until the federal funds target rate reached the zero lower bound. A set of different model explains both long and short run dynamics of U.S. money market rates up to 6 months. I find that secured money market rates move together with monetary policy expectations whereas unsecured interbank rates disconnected from policy rates due to an increase in both credit and liquidity risks.

JEL-Classification: E43; E52; E58
Keywords: Transmission of Monetary Policy, Financial Crisis, Money Market

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1 Introduction

The subprime crisis triggered a global financial crisis and severely impaired the functioning of the unsecured interbank market in 2007. This has caused serious disruptions in the transmission of monetary policy. Unsecured interbank rates decoupled from monetary policy. The U.S. Federal Reserve Bank (Fed) responded with severe target rate cuts and launched a series of non-standard monetary policy measures to improve the funding conditions in the interbank market. Therefore, the Fed closely tracked the Libor - Overnight Index Swap (LOIS) spread as a measure how interbank rates responded relative to expected monetary policy rates. Alternatively, the TED spread, the Libor over the risk-free Treasury bill (Tbill), provides another measure of money market stress. However, this measure also covers the flight-to-safety effect in government securities. Figure 1 outlines the movements of the two spreads over time. From visual inspection it can be inferred that both spreads were both small prior to the crisis. Especially, the LOIS spread was very small prior to August 2007, whereas the TED spread appears to be larger. What becomes evident from this Figure is that both spreads follow a different pattern after autumn 2008 and when the zero lower bound (ZLB) in December 2008 was reached.

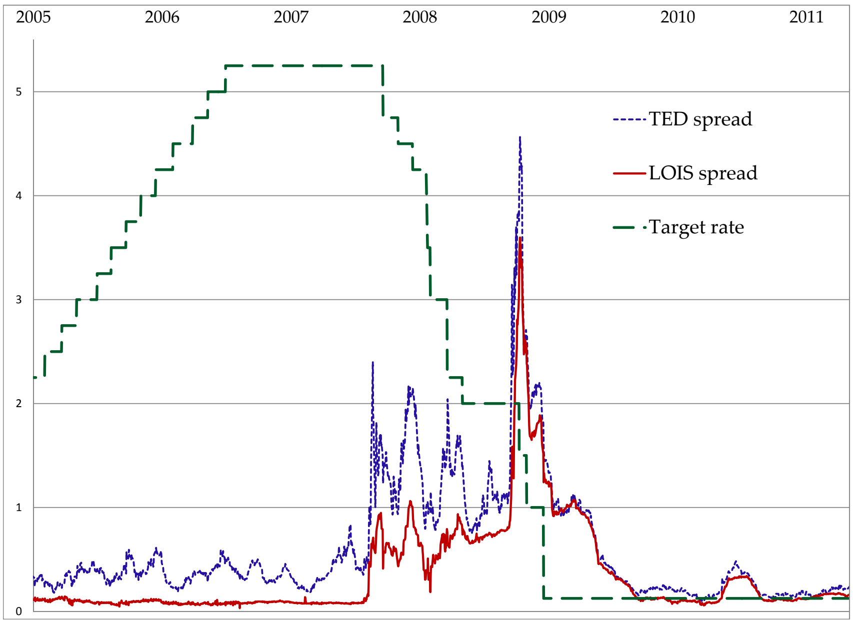

Figure 1: 3months maturity spreads (in bps)

The main objective of this paper is to evaluate the interest rate channel and to understand the dynamics in the money market in a crisis environment. I focus on the time period until December 2008 and analyse both the short and long-run adjustment of different money market instruments up to 6 months maturity. With respect to crisis and pre-crisis literature, I employ three different empirical models to evaluate how the interest rate channel is affected in an environment of high uncertainty about funding conditions.

First, in line with the crisis literature, I examine the interrelationship between Libor spreads during the financial crisis and how they respond to policy announcements. I find that Libor spreads co-move during the crisis period up to 6 months maturity due to the link between monetary policy expectations and secured interbank rates. Second, similar to pre-crisis pass-through models, I investigate the interest rate channel by estimating the long-run relationship of unsecured interbank rates, monetary policy expectations, and risks. I find that the relationship deteriorated since rates are subject to additional drivers such as credit and liquidity risk. The third approach concentrates on the dynamics of the interbank rates during the crisis. I investigate how interbank rates respond to monetary policy, liquidity and credit risk shocks. Findings show that the interbank rate respond to the shocks in credit risk and monetary policy expectations.

The remainder of this paper is organised as follows. In Section 2 I briefly summarise the literature about monetary policy transmission both prior and during the crisis. Section 3 presents the data and preliminary tests. Section 4 documents the empirical analysis including three different econometric approaches. Section 5 documents and discusses the findings. Finally, section 6 concludes.

2 Literature Review

The money markets play a crucial role in the transmission of monetary policy. By controlling the amount of reserves, most central banks set a short-term rate and rates at the longer end of the yield curve convey information about expected path of monetary policy. The concept of the expectation hypothesis explains how interest rates are tied together. In the U.S., the effective federal funds rate is the average overnight rate at which regulated financial institution lend balances among each other to meet their reserve requirements[1] at the Fed. The central bank announces a price for these reserves, the overnight federal funds target rate. Through the implementation of the monetary policy such as open market operations (OMO), temporary or permanent, the Fed determines the level of reserves and therefore steers the level of the effective federal funds rate. The next step is that expectations about future changes in the overnight rate affect the level of longer-term interest rates such as the Libor. The Libor is the reference rate for the unsecured money market and has become the benchmark for the pricing a large number of various financial contracts thereby affecting other segments of the broader financial markets and the entire economy. This transmission mechanism is called the interest rate channel. The crisis deeply distorted this channel. On August 9, 2007 when the French bank BNP Paribas announced its losses associated to toxic assets on U.S. subprime mortgages, it marked the beginning of the financial crisis which generated uncertainty about funding costs in the interbank market. Spreads between secured and unsecured interbank rates at 3 months maturity mirrored the stress in the money markets. The Fed's effort to ease market conditions through OMO did not improve the tight funding situation in the interbank market. Due to the increase in uncertainty about the counterparty risk, financial institutions became reluctant to lend among each other. The Fed launched several programmes such as the Term Auction Facility (TAF). The auction mechanism, similar to repurchase agreements (Repo) but with more counterparties admitted, with a maturity of 28 days, was however neutralised through OMO, so that the liquidity in the financial system remained unchanged. After the bankruptcy of Lehman Brothers in fall 2008, disruptions on the interbank market intensified. Due to intense surge for liquidity, the Fed was no longer able to sterilise the liquidity injections by OMO. As

[1]Reserve requirements are the amount of funds that a bank must hold in reserves against specified deposit liabilities on average over a maintenance period of two weeks.

a result, the increased liquidity in the system put pressure on the effective federal funds rate. To provide a floor for the federal funds rate the central bank started paying interest rates on both required and excess reserves starting with the maintenance period beginning on October 9, 2008. Nevertheless, on December 16, 2008 the target rate reached a near zero target range, the so-called zero lower bound. In order to further ease market conditions, the Fed started purchasing assets with medium and long maturities (see i.e. Gagnon et al. [2010]). Over the first half of the year 2009, money market spreads declined steadily (see Figure 1).

The financial crisis of 2007 to 2008, its distortions in the money markets and the effects of the unconventional measures by the central banks resulted in a large branch of literature. This section is divided into two parts, First it provide a brief overview of the crisis literature.[2] Next, it summaries empirical work about the transmission of monetary policy prior to the crisis and how monetary policy implementation affects the interest rate channel.

2.1 Money market spreads and the financial crisis

Empirical results about the reason for the elevated LOIS spread and the effectiveness of the Fed's liquidity programmes are controversial. Studying the period prior to fall 2008, the first stream of literature (i.a. McAndrews et al. [2008], Wu [2008], Michaud and Upper [2008]) employs a type of event studies and merely conclude that the spread corresponds to both increased liquidity[3] and counterparty risk, while Taylor and Williams [2009] finds the TAF measures to be ineffective and finds evidence of increased counterparty risk. In Europe i.a. Schwarz [2010]; Abbassi and Linzert [2012]; or de Socio [2013] attribute some of the spreads increase to liquidity risk. Most papers use a measure of financial credit default spreads as an approximation of counterparty risk, whereas measuring the liquidity component in the spreads more difficult. Some work, i.e. of England [2007], simply decompose the spread into a credit and noncredit risk component by subtracting the counterparty risk measure and assume orthogonally between the components. This methodology, however, can cause problems as risk measure are highly correlated and an instrument as for example the credit default swaps spread is likely to reflect liquidity risk as well. The difficulty in the spreads' decomposition into a liquidity and credit risk component, switches attention to the theoretical literature which describes how shocks can dry up market-wide liquidity. Heider et al. [2009] examines how counterparty risk can affect interbank markets and result in a reduction in liquidity due to adverse selection and market participants can no longer distinguish between good or bad counterparties. Uncertainty increases and markets may freeze. Furfine [2001] models the overnight market and shows how a certain level of counterparty risk and hence increased borrowing costs can prevent others participants from entering the market. Other literature including Allen et al. [2009] focus on the role of liquidity hoarding and conclude that banks are unwilling to lend due to precautionary reasons regardless the borrower quality of other market participants. Brunnermeier and Pedersen [2009] analyse the effects of market liquidity shocks and explain the link between funding and market liquidity during a crisis.

[2] For a detailed discussion of the literature and measures adopted by the Fed please see to Cecioni et al. [2011]

[3] Most researchers refer to the concept of funding liquidity. Funding liquidity risk is agent-specific, whereas market liquidity risk depends on the asset. These measures, however, are related (see Brunnermeier and Pedersen [2009]). For a description about funding and market liquidity risk see BIS [2008].

Another branch of literature examines the tensions in the overnight market during the crisis empirically. For further information see Bech and Klee [2010]; Afonso et al. [2011] or for Europe Beirne [2012].

2.2 Monetary policy transmission and implementation prior to the crisis

Interest rates tend to move together. This subject has been broadly studied in economics and finance. For monetary policy transmission, understanding the relationship between the overnight rate and money market rates is of major concern. Prior to autumn 2008, the Federal Reserve implemented monetary policy by targeting the effective Fed funds rate and hence, by controlling the supply of reserves. Followed by the expectations about actual and expected future federal funds rates, the central bank steered the movements to longer-term rates. Since 2007 the attention paid on the dynamics of money markets rates has increased due to its dominant role in the transmission mechanism. Two branches of literature are presented below. First, the pass-through mechanism from shorter to longer term rates and the associated literature is outlined. Second, given the importance of the proper functioning of the overnight markets, a brief summary of papers on the federal funds dynamics are documented.

2.2.1 Expectation hypothesis and the money market rates

As mentioned before, typically, one attributes the co-movements of interest rates to the theory of the expectation hypothesis. According to the expectation hypothesis it is assumed that longer-term interest rates are determined by an average of current and expected future short-term rates plus a time-invariant, constant term premium. The theory implies that the short and longer term rates co-move proportionally in the long-run equilibrium but possibly diverge in the short-run. Campbell and Shiller [1987] argue that the spread between two rates measures anticipated changes in short-term interest rates. In other words, the information inherent in the spread forecast changes in the short rates. They refer to the market participants' forward-looking behavior. Stock and Watson [1988] refer to a common stochastic trend driving the interest rates. Evidence for the expectation hypothesis, especially in the case of the effective federal funds rate as short-term interest rate, is mostly weak. Although, the interest rates mostly move tandem in the long-run, they do not move proportionally (see Sarno and Thornton [2003]). Previous literature interprets this finding as a rejection of the expectations hypothesis and concludes the presence of a time-varying term premium. Cointegration and error correction models are a possible way to assess the relationship between interest rates. The forces that generate a long-run relation between rates at different maturities imply a mean reversion of the interest rate spread and the existence of an error correction model which defines the dynamic relationship between two (or more) rates. Some of the papers argue that the strength of the link between interest rates has not been constant through time, and depends on the targeting procedure of the federal funds rate (see i.a. Hall et al. [1992], Zhou [2007]). Analysing Treasury yields, Hall et al. [1992] find that under uncertainty, the cointegration relationship may break due to an additional trend. Similarly, IMF [2008] find a break the long-run pass-through between effective federal funds rate and Libor as a response to the money market turmoil in 2007. Another branch of literature examines the pass-through mechanism from money market rates to bank retail rates (see i.e. de Bondt [2005], Biefang-Frisancho Mariscal and Howells [2011]).

2.2.2 Federal funds rate dynamics

Due to the importance of the federal funds market in conducting the monetary policy, I present previous literature about the overnight market and the implementation of monetary policy. In the U.S., the effective federal funds rate is the first stage for the monetary policy transmission. Since the 1980's the Fed has had a target for the federal funds rate. However, only after 1994 the FOMC decisions about a target rate changes were announced right after the meeting which has drawn more attention to the federal funds behaviour. In 2000 the Fed enhanced its communication with the introduction of the so-called balance of risk statement which has improved transparency of the policy [Ehrmann and Fratzscher, 2007]. In terms of reserve requirements, the Fed changed from contemporaneous to the lagged reserve computation in 1998. Under contemporaneous reserve computation depository institution did only knew their level of reserve requirements on the day prior to the end of maintenance period. Whereas under the lagged reserve computation practice, banks know the level of required reserves in advance of a maintenance period. Previous literature, mostly following the seminal paper of Hamilton [1996], show how central bank's operational framework, communication or the reserve requirement can influence both mean and volatility of the federal funds rate. As monetary policy in the U.S. has become more transparent and predictable, the anticipation of changes to the target rate led to movements in the funds rate before many target rate changes. The role of expectations in the reserve market was analysed by Taylor [2001]. Demiralp and Jordá [2004] demonstrate the importance of the announcement effects after 1994, in contrast to the conventional liquidity effect. Nautz and Schmidt [2009] find that increased transparency since 1994 has influenced the dynamics of the federal funds rate. Volatility in the overnight market is mostly associated with banks' daily liquidity management rather than the path of future monetary policy, but communication and implementation may also affect the overnight volatility. Thus, Nautz and Schmidt [2009] find that communication and transparency also improved federal funds volatility. Additionally, their findings indicate that federal funds volatility negatively depends on the level of required reserves on total deposits. Other papers also examine the volatility transmission from overnight to longer term money markets (see i.e. Ayuso et al. [1997], Wetherilt [2003], Lee [2006], Nautz and Offermanns [2008], Colarossi and Zaghini [2009]). Since volatility in the overnight market can blur signals about the future stance of monetary policy, excess volatility and potential transmission to longer term rates has to be avoided. In extreme circumstances, it can affect how well the central bank is able to steer the interest rates, causing a loss of the central bank's credibility in conducting monetary policy. In Europe, Nautz and Offermanns [2008] find a significant volatility transmission even for the twelve-month money market rates; distinguishing between seasonal volatility and non-seasonal volatility. Whereas seasonal volatility in the overnight market associated with e.g. the end of the maintenance period effects, is not transmitted to longer term interest rates, non-seasonal volatility[4] is transmitted along the yield curve. According to them, this may indicate that transmission of overnight volatility along the yield curve is a relevant issue in case they reflect uncertainty about monetary policy.

[4]Conditional Eonia variance estimated at days unrelated to seasonal effects.

Colarossi and Zaghini [2009] find that the volatility transmission in the U.S. has disappeared after 2000. However, they also attribute this finding to other reasons such as the period of moderation in macroeconomic developments or innovations in the financial markets which may have contributed to the low interest rate volatility until the onset of the financial crisis in 2007.

3 Data and preliminary tests

Before presenting the three empirical models to obtain insights about the interest rate channel, I briefly present the data and tests to determine the order of integration of the time series. The table in the Appendix A.1 provides an overview and description of the data in this paper. The data covers instruments used in previous studies. My analysis covers a daily frequency sample on U.S. money market rates for 1, 3 and 6 months from 03/03/2003 to 12/15/2008. The starting point of this analysis is an eye inspection of the dynamics of various secured but also unsecured money market rates. Figure 2 plots the difference between the overnight index swap rate and the Tbill which is likely to indicate a permanent change around the end 2008. The zero lower bound and the dramatic increase in the Fed's balance sheet mark the start of a new operational framework. Figure 2 also presents the dynamics of 3month Libor, OIS and Tbill over the last ten years. Secured rates such as the Tbill were also disrupted after August 2007 but less heavily than unsecured interbank funding rates. Hence, the break given by the operational change in monetary policy is more easily detected in their difference[5].

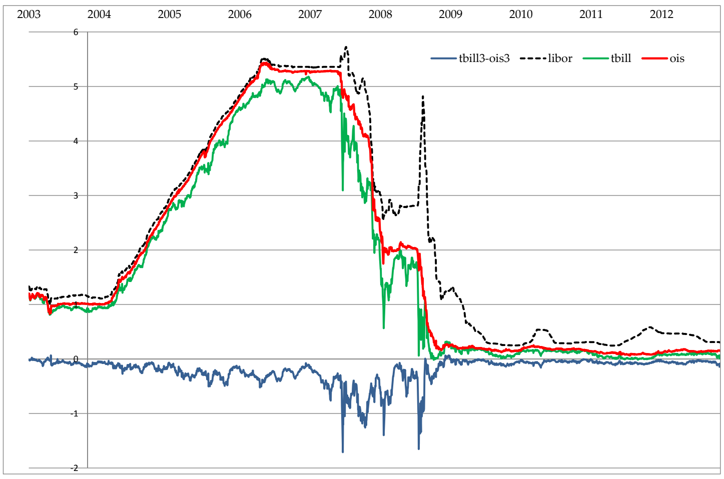

Figure 2: Rates at 3months maturity (in bps) and the Tbill-OIS spread

In summary, the following money market rates and measures of risk are included in my empirical study:

- Unsecured interbank rates: Libor, Eurodollar, and certificate of deposit rate

Libor is the London interbank offered rate. Calculated by daily survey of international banks in London just prior to 11 a.m. Eurodollar on the other hand, are best offered rates on offshore USD Certificate of deposit (CD) brokered by ICAP around 9.30 a.m. in New York[6]. Certificate

[5]In line with this, also Bech et al. [2012] find that the pass-through from the federal funds rate to the overnight GC Repo deteriorated at the ZLB as response of limited arbitrage and idiosyncratic market factors.

[6]See Gyntelberg and Wooldridge [2008] who assess the fixing of the different interbank rates.

of deposits are another funding source on the interbank market offered to individuals in the U.S..

- Secured money market rates: Tbill, GC Repo rate

Government securities as the Tbills are due to their market liquidity, favourable tax treatment[7] and lack of default risks, popular money market rates. Thus, the range of investors is rather heterogeneous. During times of stress, investors shift their attention to first-rate collateral, which results in a flight-to-safety effect [McCauley and McGuire, 2009]. General collateral repurchase agreements are secured financial contracts that allow borrowers to use Tbills as collateral for cash loans at a fixed interest rates [Hördahl and King, 2008]. Bloomberg, however, only offers ICAP brokered GC Repo rates at 3months maturity.

- Monetary policy expectations: OIS rate

A OIS is a interest rate swap contract that consists of a floating and a fixed rate leg. The floating rate is tied to the the geometric average of the effective federal funds rate over each time interval of the contract. At maturity of the contract, the two counterparties swap the difference between interest accrued at an pre-determined fixed rate and the floating rate on the notional amount of the contract. Therefore, the fixed rate reflects the expected Federal funds rate over the term of the swap plus a small premium. The counterparty paying the floating rate bears the risk of future interest changes. On the other hand, the contract ensures longer-term funding near the overnight rate and hence the investor agrees on paying a premium, rather than rolling funds on a daily basis [see Sengupta and Tam, 2008]. The term OIS rate refers to the fixed rate of the contract. Rather than using the federal funds rate, I employ models with a measure of expected monetary policy over the same term as the unsecured rates. In line with the expectation hypothesis, subtracting the OIS rate from unsecured interbank rates, the spread should then represent a pure measure of interbank risk [Taylor and Williams, 2009].

- Credit risk: Median of 5years credit default swap spreads

The median of credit default swap spreads is calculated from the Libor panel banks following previous literature such as Taylor and Williams [2009]. For detailed information about the credit default swaps refer to Blanco et al. [2005].

- Liquidity measures: Federal funds rate volatility

The first source of liquidity for banks is the overnight federal funds market where the operating framework of the Fed is designed to meet the banks' demand for reserves. The market's important role is highlighted in the literature review. Volatility in overnight market can create uncertainty over funding costs and blur the signals from monetary policy. In this paper I distinguish between two different measures of the overnight volatility; realised and implied volatility (IV). Note that various other papers also investigate the conditional volatility computed from GARCH models [Ayuso et al., 1997]. A drawback of the conditional volatility is that it relies on

[7] Income tax on Treasury bills is exempt from both state and local income taxes.

the model specifications and may be sensitive to breaks. Therefore, realised volatility provides a more reliable estimate of the observed overnight volatility. In this paper, the realised federal funds volatility is estimated as the mean absolute deviation from the target rate over the past 30 days [see Hilton, 2005, Carpenter and Demiralp, 2011][8]. In contrast, the IV derived from options of federal funds futures is related to the realised volatility and can be seen as predictors of the realised volatility [Neely, 2004]. Since federal funds futures measure the average expected federal funds rate over a month, I derive the IV from the second Nearby contract in order to not to infer with realised volatility.

Referring to theoretical papers summarised in the literature review under 2.1, one has to bear in mind, that volatility in the overnight market and counterparty risk can be related. Uncertainty about counterparty risk may encourage financial institutions to hoard excess reserves and cause an evaporation of the market liquidity [see e.g. Heider et al., 2009]. According to Carpenter and Demiralp [2011], realised volatility explains major parts of the 3 months LOIS spread. Figure 3 shows the LOIS spread relative to CDS median and the absolute daily deviation of federal funds rate from the target rate. The black line represents the target rate change to the range of 0 to 0.25 percent (ZLB) on December 16, 2008. One can observe that the CDS measure remains elevated after December 2008 but the LOIS spread declines in 2009.

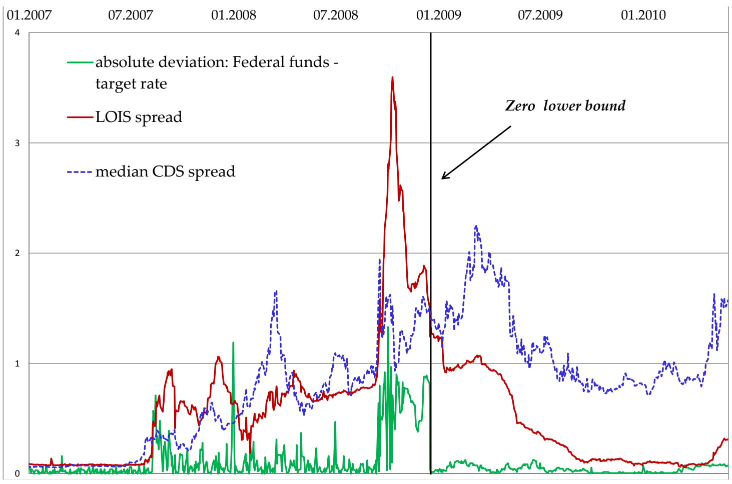

Figure 3: LOIS spread at 3months maturity (in bps) and risk measures

[8]Papers such as Carpenter and Demiralp [2011] or Durré and Nardelli [2008] calculate realised volatility from intraday data. Series for federal funds intraday volatility can be collected on: www.newyorkfed.org/markets/omo/dmm/fedfundsdata.cfm

3.1 Order of integration

To examine the long-run properties between interest rates, it is necessary to test for a stochastic trend in the first place. However, by definition of conventional economic and finance theory bounded variables like interest rates should be stationary. Having said that, various researchers treat interest rates as integrated processes. Empirical literature on interest rates, starting with Engle and Granger [1987], either assumes or finds that interest rates to be nonstationary. Moreover, Hall et al. [1992] shows that even interest rate spreads of different maturity can become nonstationary during time of stress. In order to determine the order of integration, I apply different unit root and stationarity tests; such as the Augmented Dickey fuller (ADF), the Phillips-Perron (PP), the Kwiatowski-Phillips-Schmid-Shin (KPSS) and Elliott-Rothenberg-Stock (ERS). All tests are computed on the level and on first differences. Also, Schwartz (SBC) as well as Akaike (AIC) criterion are considered in ADF and ERS tests. The Appendix A.2 provides a short description of the tests. All tests are performed at 5 per cent significance level. A potential drawback of the standard unit root and stationarity tests is that they may be biased in the presence of structural breaks. I circumvent this problem by testing different sub periods: entire sample: 03/03/2003 - 12/15/2008, pre-crisis: 03/03/2003 - 08/08/2007, and crisis 08/09/2007 - 12/15/2008. Findings are summarised in the Appendix A.2. A summary of the tests on the spread between secured and unsecured rates is listed in Table 1. As discussed in Hall et al. [1992] the H0 for an unit root cannot be rejected for ADF, PP and ERS and the H0 of stationarity can mostly be rejected at 5 per cent[9]. Moreover, the test statistics for the pre-crisis period concerning the realised federal funds rate volatility show mixed results. When determining the lag length with SBC criterion, the time series is clearly I(0) for ADF, ERS and PP. Lag length by AIC, on the other hand, indicates that the volatility contains a stochastic trend. However, based on the findings, I assume all series to be I(1) and this motivates the investigation of common trends.

		LOIS			**TED**			**REPO spread**
		1M	**3M**	**6M**	**1M**	**3M**	**6M**	3M
08/09/2007 - 12/15/2008								
ADF[a]	**LEVEL**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**
	DIFFERENCE	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)
PP	**LEVEL**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**
	DIFFERENCE	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)
ERS[a]	**LEVEL**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**
	DIFFERENCE	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)
KPSS	**LEVEL**	**I(1)**	**I(1)**	**I(1)**	**I(0)**	**I(1)**	**I(1)**	**I(1)**
	DIFFERENCE	I(0)	I(0)	I(0)	-	I(0)	I(0)	I(0)

Notes: [a] lag length with AIC, SBC. Tests performed at 5 per cent significance level.

Table 1: Order of integration during the crisis

[9]Only the TED spread at 1month maturity is found to be I(0) following the KPSS methodology.

4 Empirical analysis

The major objective of this paper is to gain insights about the interest rate channel. This section describes three models analysing the behaviour of the money market rates in the short and long-run. First, estimating a bivariate framework, I evaluate the dynamics of Libor spreads during the crisis. The movements of the different Libor spreads as indicator of interbank health were analysed intensively in previous literature. The first model estimates the joint dynamics and measures possible effects from monetary policy actions. Second, with respect to previous pass-through models, I examine the movements of the interbank rates, both in mean and volatility, allowing for additional long-run trends in the mean. The sample covers a longer observation period including both pre-crisis and the crisis until December 2008. Third, I estimate a reduced form VAR over the crisis period. In order not to impose too many restrictions, the long-run properties in the data are not explicitly modeled. Within this framework I analyse how the interbank rates at different maturities react to unexpected movements liquidity, and credit risk but also to shocks in expectations about future path of monetary policy.

4.1 Bivariate VECM

Since initial testing indicated that money market spreads are I(1), a bivariate Vector Error Correction Model (VECM) is specified to model the relationship between LOIS and either TED or Repo spread during the crisis. The aim of this approach is to analyse whether the money markets share a common trend. In case of the LOIS spread, the expected future policy rates are deducted, so that the spread should represent a pure measure of risk. The TED spread, however, is more likely to represent the flight to quality effect in the secured treasury market. Tbills are link to the monetary policy through the Repo market, where they serve as a collateral. Therefore, subsequently I also analyse dynamics between the LOIS spread and the spread between the Libor and GC Repo rates. Taylor and Williams [2009] use this spread as measure of credit risk by subtracting the secured funding rate for financial institutions from the unsecured Libor rate. However, the GC Repo rates are affected by liquidity risk too as they are linked to the underlying collateral (see i.a. Hördahl and King [2008]). So, if spreads are cointegrated, the pass through from monetary policy to secured rates, represented by the relationship between OIS and Tbill, Repo respectively, continued. As discussed previously, I estimate a reduced crisis sample: 08/09/2007 to 12/15/2008.

I first tested for cointegration with the two-step by Engle-Granger and Phillips-Ouliaris approaches. Further information about the testing procedure as well as the outputs are reported in the Appendix A.3. Then, I estimate a bivariate reduced-form VAR to determine the number of lags for the Johansen test. The lag length is first selected with the more parsimonious SBC in order to avoid overfitting the model. If the Lagrange multiplier test statistics reveal remaining reasonable autocorrelation in the residuals, Hannah Quinn (HQ), AIC and then LR statistic are taken into account.[10] This procedure is repeated until the residuals appear to be white noise. Finally, the stability of the VAR is considered by checking the inverse roots of the AR

[10]Overparametrisation is considered to be larger problem than remaining autocorrelation after ten business days.

Exogenous variables	Proxy for	Literature	expected impact
d(fftr) [b]	Immediate short-run pass-through effect after a target change.	i.a. Bartolini and Prati, 2006	+
D [taf]	Term auction facility announcements by the FED.	McAndrews, 2009 and Carpenter et al., 2013	-
news [c]	Macro news to account for other announcement effects than target changes: Surprise component subtracted from consumer confidence, retail sales, production and unemployment	i.a. Andersen et al. 2002; Ehrmann and Fratzscher, 2007; Moessner and Nelson, 2008	+/-
X	End of month, quarter, year and events. Dummy to control for events such as Lehman.	i.a. Hamilton, 1996	+/-

Notes: [b]Other studies question the target rate to be an exogenous variables (see i.a. Thornton, 2004). [c] The macro news are calculated relative to the median of the Bloomberg survey and are normalised by their standard deviation.

Table 2: List of exogenous variables for the VECM

characteristics polynomial. Next, I perform the Johansen test. Since there are only two variables, I test for one cointegrating vector. At last, I specify the following VECM

$$\Delta ted_t = \sum_{i=1}^{p-1} \phi_{1i}^{ted} \Delta ted_{t-i} + \sum_{i=1}^{p-1} \phi_{2i}^{ted} \Delta lois_{t-i} + \alpha_1 ECT_{t-1} + \epsilon_t^{ted} \tag{1}$$

$$\Delta lois_t = \sum_{i=1}^{p-1} \phi_{1i}^{ted} \Delta lois_{t-i} + \sum_{i=1}^{p-1} \phi_{2i}^{lois} \Delta ted_{t-i} + \alpha_2 ECT_{t-1} + \epsilon_t^{lois} \tag{2}$$

$$ECT_t = ted_t - c - \beta lois_t \tag{3}$$

Adding the error correction term (ECT) to a VAR model in differences produces the VECM. The ECT, however, is restricted to a constant term. The speed of adjustments parameters, denoted by α_1 and α_2, measure the degree to which the spreads adjust to correct deviations from long-run relationship. The coefficients of ϕ measure the short-run impact. A set of exogenous variables enters the VAR to control for immediate effects on the short-run dynamics. I control for policy announcements but also the impact from macroeconomic news and calendar effects. The variables are listed separately in Table 2.

I also consider the half-life responses of both spreads after a shock. This measure gives an idea about the period of adjustment. Note that the long-run relationship estimated with β links to the speed of adjustment parameters to the cointegrating error. The error from the long-run equilibrium is an AR(1) process. Under the assumption of a VAR(1) model, the cointegration error can be modeled as in Equation 4

$$ECT_t = (1 - \alpha_1 - \alpha_2 \beta) ECT_{t-1} + \epsilon_t^{ted} + \epsilon_t^{lois} \beta \tag{4}$$

For an stationary AR(1) process, the speed of mean-reversion is measured by the half-life defined as

$$k = ln(0.5)/ln\theta \tag{5}$$

whereas in the VAR(1) case

$$\theta = 1 - \alpha_1 - \alpha_2\beta_1 \tag{6}$$

(see for example Tsay [2005], pp.49). Therefore, only if the absolute value of θ is smaller than one, the linear combination of the two variables is I(0) [Johansen, 2009, pp. 676]. It is crucial to reconsider that while the adjustments to the cointegration error may differ for each variable in terms of magnitude, the time to adjust to the new equilibrium is the same for both spreads. However, if one variable is weakly exogenous than it immediately adjust to the new equilibrium [Morley, 2007].

4.2 EGARCH model with error correction term

This model relates to the pre-crisis literature as described in literature review under 2.2.1 to 2.2.2. According to the expectations hypothesis, interest rates move together, as longer-term rates should be equal to the expected short-term rate over the same term as the longer rate plus a constant risk premium. Initial testing showed that the spread between secured and unsecured rates over the same term became nonstationary. Various paper studies this long-run relation among interest rates of different maturities using cointegration methodologies in the pre-crisis period [Hall et al., 1992, Sarno and Thornton, 2003, de Bondt, 2005, Zhou, 2007, Biefang-Frisancho Mariscal and Howells, 2011]. In line with them, this section focuses the pass-through from monetary policy including both the crisis and pre-crisis period. Since unsecured market rates disconnected from the target rate, I need additional variables to describe the long-run relationship between monetary policy and unsecured interest rates so that the residuals become stationary. Following Carpenter and Demiralp [2011] I adopt an error correction model including the realised federal funds volatility as risk premium. Their sample lasts until 2010, whereas mine only covers 2003 to 2008. Considering the dynamics of the spreads in the previous section, from a visual inspection one can see a break in the end of 2008. After the Fed had cut interest rate to zero on December 16, 2008, expectations about future monetary policy, proxied by the OIS rate, and but also the volatility in the federal funds rate were tied to the floor of the federal funds rate (see Gagnon and Sack [2014] for more information). In other words, with the interest rates at the ZLB, the Fed no longer uses the effective federal funds rate as its operational target. The traditional interest rate channel has changed and the Fed operates through other channels. These, however, are beyond the scope of this paper. I first perform residual-based cointegration tests by Engle Granger and Phillips Ouliaris. A further indication whether the variables are cointegrated is a statistically significant adjustment coefficient in the error correction model. Both tests are performed for the sample period 03/03/2003 to 12/15/2008 including both the crisis and pre-crisis period. I tested twice using AIC as well as the more parsimonious SBC criterion. I also tested the pre-crisis period, checking whether unsecured interbank rates were cointegrated with OIS rates prior to the crisis. Next, the model is estimated in two steps. First I estimate the long-run relationship of the variables with dynamic OLS (DOLS) as in

Equation 7. Next, I estimate error correction equations in a similar fashion as being estimated in the previous literature (see for example Nautz and Schmidt [2009]). I adopt an EGARCH model to analyse both the mean and the time-varying volatility of the daily unsecured interbank rates. As mentioned before, I employ a model including the realised federal funds volatility as Carpenter and Demiralp [2011]. The model of Carpenter and Demiralp [2011] is augmented in two ways. First, estimations of the long-run relation are performed with dynamic OLS (DOLS) to receive consistent, asymptotically normally distributed and efficient estimates of the cointegrating vector. This methodology by Stock and Watson [1993] results in robust estimators for small samples and corrects the bias, simultaneity and serial correlation problems. DOLS corrects for parameter and standard error bias through the addition of leads and lags of the first difference of all right-hand side variables, as shown in equation 7. Moreover, concerning the time period covered, it tends to be more robust than the Johansen methodology in the presence varying adjustments to the long-run equilibrium. In contrast, Carpenter and Demiralp [2011] estimated the level relationship with OLS.

The error correction term ECT_t can be easily calculated as in Equation 8. r_t represents the Libor at either 1, 3 or 6months maturity. For robustness, I also estimate the model with Certificate of deposit rates and offshore Eurodollar rates. The ois_t corresponds to same maturity as the unsecured rate. The ffv_t represents the realised volatility over the past 30 days.

$$r_t = \beta_0 + \beta_1 ois_t + \beta_2 ffv_t + \sum_{i=-r}^{p} \beta_3 i \Delta ois_{t-i} + \sum_{i=-r}^{p} \beta_4 i \Delta ffv_{t-i} + \vartheta_t \tag{7}$$

$$ECT_t^{dols} = r_t - \beta_0 - \beta_1 ois_t + \beta_2 ffv_t \tag{8}$$

The second modification from Carpenter and Demiralp [2011] approach is that I adopt error correction model (ECM) as in Equation 9. The ECM is modeled in standard way where the differenced unsecured interbank rate is regressed on the lagged ECT_t term and on the lagged differenced variables from long-run framework. This model specification resembles other single equation error correction models by including it in a GARCH framework to model both the mean and time-varying volatility of the daily unsecured interbank rates. Additionally I control for contemporaneous short-run impacts on both mean and also, impacts on the volatility with a set of different variables mentioned in former literature (see Table 3 for a complete list of those).

$$\begin{aligned}\Delta r_t = \sum_{i=1}^{n} \phi_{1,i} \Delta r_{t-i} + \sum_{i=1}^{o} \phi_{2,i} \Delta ois_{t-i} + \sum_{i=1}^{m} \phi_{3,i} \Delta ffv_{t-i} + \alpha ECT_{t-1}^{dols} \\ + \delta_1 fs_t + \delta_2 fs_t * D_t^{crisis} + \sum_{l=1}^{5} \delta_{3,l} D_{t,l}^{TAF} + \sum_{l=1}^{4} \delta_{4,l} news_{t,l} + \varphi' X_{1t} + \phi_0 + \sigma_t \varepsilon_t\end{aligned} \tag{9}$$

The immediate impact of the surprise in monetary policy fs_t is extracted from federal funds futures following the Kuttner [2001] methodology. The unanticipated target rate change is calculated from daily change of the first nearby contract f^0 of the federal funds futures[11]. Since a futures contract represents the average expected effective federal funds rate, one has to weigh

[11] The contract is rolled on the last business day of the month.

the change in federal funds futures contract from day $t-1$ to t. D represents the number of days of the current month and d the day of the month.

$$fs_t = \frac{D}{D-d}(f_t^0 - f_{t-1}^0) \tag{10}$$

On the first day of the month, I use the second nearby contract for the last day rather than the first. Another exemption are the last three days of the month when the unscaled difference between second nearby contracts is taken into account[12]. δ_2 controls whether the impact of an unexpected policy rate has changed during the crisis. Additionally, I follow McAndrews et al. [2008] and control for various announcement effects related to the TAF after December 2007[13]. $news$ represents a set of variables accounting for the surprise components extracted from macroeconomic releases to control for other announcements than those from the central bank. The surprise components from macroeconomic releases are calculated relative to the median of the Bloomberg survey and are normalised by their standard deviation. For both macroeconomic news and monetary policy surprises, I construct series which are set to 0 on days without news and denote for the surprise component on the announcement days.

To account for the time varying volatility and hence following other papers who have documented asymmetric responses of volatility to money market rates shocks, I estimate an exponential GARCH model (EGARCH). Since this augmented GARCH model estimates the conditional variance process in logs, there is no need for non negativity constraints. Additionally, the EGARCH benefits from additional leverage terms to capture the asymmetry in volatility clustering. Following the seminal paper of Hamilton [1996], who suggests that Federal funds rate volatility is characterised by asymmetric responses to interest rate shocks, other work apply the similar approach for money market rates, especially for Treasury securities (see i.a. Ayuso et al. [1997], Ehrmann and Fratzscher [2007], Lee [2006]). The sample period is longer than in the other two models. The reason for this is twofold. First, it allows estimating the interest rate channel in both the pre-crisis and crisis period and second, due to possible structural breaks in the sample during the crisis, GARCH models respond slowly and a larger amount of data is required . The volatility Equation 11 is estimated as follows:

$$\begin{aligned} log(\sigma_t^2) = w + \gamma_1 \mid \frac{\varepsilon_{t-1}}{\sigma_{t-1}} \mid + \gamma_2 \frac{\varepsilon_{t-1}}{\sigma_{t-1}} + \gamma_3 log(\sigma_{t-1}^2) \\ + \upsilon_1 \mid fs_t \mid + \upsilon_2 \mid fs_t \mid D_t^{crisis} + \sum_{l=1}^{5} \upsilon_{3,l} D_{t,l}^{TAF} + \sum_{l=1}^{4} \upsilon_{4,l} \mid news_{t,l} \mid \\ + \upsilon_5 D_t^{FOMC} + \upsilon_6 D_t^{crisis} + \upsilon_7 D_t^{IOR} + \upsilon_8 D_t^{postLB} + \theta' X_{2t} + \epsilon_t \end{aligned} \tag{11}$$

The conditional variance and the conditional mean equation, are jointly estimated with the Quasi maximum likelihood technique. There are leverage effects if the γ_2 is statistically significant. Ehrmann and Fratzscher [2007] state it is possible that monetary policy announcements may provoke an immediate positive reaction on the mean of the rates and at the same reduce uncertainty as reflected in conditional volatility over time. If markets know the future path of

[12]It is assumed that there are no more than one target change each month.
[13]The set of TAF dummy variables are the same as for the bivariate VECM.

monetary policy, there are relatively small effects on conditional market volatility after a target rate change. Therefore as in the mean equation, I control whether absolute policy surprises fs_t affect interest rate volatility. Also, I control whether the absolute impact on interest rate volatility after an unexpected policy rate change has increased during the crisis. Dummies account for increased volatility on the FOMC meetings days or overall heightened uncertainty during the crisis and another shift dummy for the period after the collapse of Lehman Brothers. Plus, I augment the model with a shift dummy D_t^{IOR} to investigate the impact of the introduction of the remunerated reserves on interest rate volatility. Nautz and Schmidt [2009] suggested the introduction of remunerated reserves to have a negative impact on federal funds volatility and since realised volatility increased risk premium in the mean, I also control whether it has an negative effect on the longer term interbank rates volatility. A set of dummy variables Xt captures the possible calendar effects of the volatility of the unsecured interbank rates and for events such as August 9, 2007 to capture outliers. Additionally, as in the mean equation, the volatility equations is also control for the impact of releases about macroeconomic fundamentals. The short-run impact variables on the mean as well as the variables in the volatility equation and their expected impact are summarised in Table 3.

This methodology differs from previous studies about the interest rate channel since they mostly analyse the monetary transmission from shorter to longer term interest rates. One possible drawback is outlined in previous bivariate (or multivariate) studies such as Sarno and Thornton [2003] who often argue that the policy rate adjusts to the longer term rates, whereas the longer term rates is weakly exogenous. One explanation is given by the argument that longer term rates contain information about future short term rate [Campbell and Shiller, 1987]. The expected path of monetary policy is proxied by the OIS rate over the maturity as the unsecured rate and it is therefore more likely to assume that money market rates adjusts to their changes. By including a variables to proxy risk premium, this modeling framework allows studying the long-run transmission of monetary policy to unsecured interbank rates and their speed of adjustments to the new equilibrium. Moreover, the use of different interbank instruments enables to compare the Libor rate. Especially, I am interested in the speed of adjustment of the CD rates at various maturities in comparison to the Libor and ED rate. If financial institutions were liquidity constrained, the CD market, where lenders are non-banks, should adjust more strongly to restore the equilibrium relationship.

Variables	Proxy for	Literature	expected impact
Mean Eq.			
fs	Immediate short-run pass-through, surprise component from FF futures.	Kuttner, 2001	+
$D^{(taf)}$	A set of variables to capture possible effects from the announcements of TAF.	McAndrews, 2009 and Carpenter et al. 2013	-
news	Macro news to account for other announcement effects : Surprise component subtracted from consumer confidence, retail sales, production and unemployment.	i.a. Anderesen et al., 2007; Ehrmann and Fratzscher, 2007; Moessner and Nelson, 2008	+ [b]
X	Calendar effects: end of month, quarter and year and dummies to control for events outliers.		+/-
Volatility Eq.			
D^{TAF}	TAF effects could either calm markets or create higher uncertainty.		+/-
$\|fs\|$	Absolute surprise component of target rate change from FF futures.	i.a. Kuttner, 2001; Lee, 2006; Nautz and Schmidt, 2009	+
D^{crisis}	Accounting for the heightened uncertainty in financial markets – shift dummy from Aug 9, 2007.		+
D^{postLB}	Shift Dummy to account for the heightended uncertainty following the collapse of Lehman on Sept 15, 2008.		+
D^{IOR}	Denotes for 1 after the launch of remunerated reserves on Oct 9, 2008.		-
$\|news\|$	According to Andersen et al., 2007 volatility tends to be highest around macro announcements.	i.a. Ehrmann and Fratzscher, 2007; Andersen et al. 2007	+
D^{FOMC}	Accounting for the heightened uncertainty at FOMC meeting days.		+
X	Calendar effects: end of month, quarter and year and uncertainty around specific events.		+

Notes: [b] Unemployment is expected to reduce the mean.

Table 3: List of variables in EGARCH model

4.3 VAR on levels

Whereas the previous models distinguished between permanent and transitory components of the dynamics, within this subsection a simple reduced-form vector autoregressive (VAR) model is fitted to levels despite the variables' unit roots. This is a common approach in VAR modeling, ignoring long-run properties in order not to impose too many restrictions which could appear when imposing inappropriate cointegration relations and hence, could lead to biased estimates. The aim of this model is to estimate the dynamics of the money market rates to an unexpected shock in the levels. To investigate the dynamic response following a shock, I estimate both impulse response functions and conclude the analysis with a forecast variance decomposition. The lag length selection is the same as described in the VECM estimating. Based on this methodology I specify a VAR at each maturity of 1, 3 and 6 months, respectively.

$$Y_t = c + \sum_{i=1}^{p} A_i Y_{t-i} + \epsilon_t \tag{12}$$

The vector Y_t in Equation 12 accounts for 4 endogenous variables. ϵ_t denotes the vector of residuals. c is a 4x1 vector of intercepts. Also, dummy variables to control for calendar effects and outlier events are included (not shown in Equation 12). Y_t includes: unsecured interbank rates, the OIS rate to proxy market expectation for future monetary policy, again the median CDS spread of major Libor panel banks and the implied volatility extracted from federal funds futures options to proxy uncertainty about funding risk. The main focus of this modeling framework is on the adjustment of the unsecured interbank rates to an unexpected shock during the financial crisis prior to the ZLB. I estimate a model for each maturity and interest rate to compare the impacts at different maturities and instruments[14]. In order to obtain innovation accounting, Cholesky decomposition of the residual variance covariance matrix is used to identify extract orthogonal shocks from the residuals. The output following a Cholesky decomposition relies very much on the ordering of the variables. Hence, different ordering is considered. Then, impulse response functions (IRF) or forecast error impulse responses are obtained to measure the impact of the variables to one unit of shock over time. All variables are integrated of order one and therefore they are all subject to permanent shocks. I chose the unsecured interbank rate to have immediate impact from all other shocks. I consider a forecast horizon up to a month. Further, the forecast error variances decomposition shows the contribution of the movements due to its innovations relative to other shocks. Additionally, I also perform Granger causality (GC) tests to analyse the interrelationship between variables. For the GC testing I rely on the methodology of Toda and Yamamoto [1995].

[14]In order to keep the model as lean as possible the model is restricted to those 4 variables. One could argue that additional variables were useful.

5 Findings

This section documents and discusses the findings from the three models presented above.

5.1 Co-movements of the money market spreads: 2007 to 2008

Given the importance of the LOIS and other Libor spreads during the crisis, I analyse their joint dynamics in this section. At first, both Johansen and residual based tests give evidence of a cointegration relationship between TED and LOIS spread at different maturities, but also between Repo and LOIS spread (see Appendix A.3 and A.4). Table 4 represents the outputs without exogenous control variables[15]. All statistically significant adjustment coefficients are correctly signed. The coefficient for the LOIS spread is weakly exogenous with respect to the cointegrating relationship[16]. Meaning that the LOIS spread does not adjust to deviations from the equilibrium. The TED spread adjustment parameter, however, is significant and negative. Replacing the TED with the Repo spread, one obtains similar results. However, the long-run coefficient is larger which indicates stronger co-movements. The results imply that deviations in the TED spread from long-run equilibrium have a half-life of roughly 7 to 8 days at all maturity whereas the Repo spread only requires around 3 days. The adjustment in the Repo spread is clearly faster than in the TED spread. This finding is no surprise as the Repo and OIS rate are both financial instruments from the interbank market whereas the Treasury market also attracts other investors. An interesting finding, however, is that there is no difference between the maturity of the instruments. It seems as all term markets were impaired. Moreover, the positive constant indicate a mark up for the liquidity risk between Tbill and OIS, Repo and OIS rate respectively. I also estimated models for between OIS and Tbill or Repo rate. Both cointegration tests and the model indicate a linear relationship. A model for Repo and OIS rate for a reduced sample period prior to the Lehman collapse shows stronger co-movement of the two rates and an one-to-one relationship between the rates, but with a lower speed of adjustment. A possible explanation may be that over this short sample period, tight market conditions and increased liquidity provision by the central bank weakened the interest rate channel to secured rates.

The money market spreads adjust to the expectations of the future path of monetary policy. I augment the model with a set of exogenous variables. Following crisis-literature such as McAndrews et al. [2008] I control for the effects of policy announcements and whether they influence (i) the speed of adjustment or (iii) the short-run dynamics of the money market spreads. Additionally, I also add variables to control for calendar effects or effects from economic news. The output of the augmented model with exogenous variables is listed in Table 2. The results from the augmented model in Table 5 do not differ from those in Table 4 considerably, despite decreasing the speed of adjustments slightly. As stated by Taylor and Williams [2009] if the risk premium in unsecured markets was dominated by uncertainty about counterparty risk rather than liquidity risk, the launch of liquidity programmes could hardly improve market conditions.

[15] The model is subject to ARCH effects. Since linear dynamics of the spreads are of main interest in this model, this property was not modeled [Lütkepohl and Krätzig, 2004].

[16] LR test for H0 of α_2=0 as proposed by Johansen were conducted. The H0 cannot be rejected for any model. Hence, in all cases the LOIS spread is weakly exogenous with respect to the cointegrating relationship.

	long-run β	constant c	speed of adjustment α_1	α_2	Half-life k^b	Lags (in diff.)
08/09/2007 - 12/15/2008						
TED - LOIS						
1M	1.076(***)	0.699(***)	-0.089(***)	0.01	7.4	2
3M	0.706(***)	0.835(***)	-0.086(***)	-0.005	7.7	4
6M	0.633(***)	0.675(***)	-0.085(***)	0	7.8	2
Repo spread - LOIS						
3M	0.868(***)	0.322(***)	-0.234(***)	-0.011	2.6	4
Tbill - OIS[a]						
1M	0.831(***)	-0.299	-0.135(***)	0.004	4.8	6
3M	0.843(***)	-0.179	-0.125(***)	-0.002	5.2	6
6M	0.822(***)	-0.145	-0.122(***)	-0.035(*)	5.3	2
Repo - OIS[a]						
3M	0.95(***)	-0.053	-0.240(***)	-0.012	2.5	7
08/09/2007 - 08/30/2008						
Repo - OIS[a]						
3M	1.003(***)	0.239	-0.162(***)	0.0	3.92	6

Notes: [a] LR tests suggest a drift term in the VAR on differences. [b] $|\theta|<1$.
(*), (**), and (***) denotes significance at 10, 5, and 1%.

Table 4: VECM spreads without exogenous variables

	long-run β	constant c	speed of adjustment α_1	α_2	Half-life k^b	Lags (in diff.)
08/09/2007 - 12/15/2008						
TED - LOIS						
1M	1.085(***)	0.73(***)	-0.083(***)	0.0	8.7	2
3M	0.689(***)	0.918(***)	-0.085(***)	0.0	8.5	4
6M	0.633(***)	0.70(***)	-0.084(***)	0.0	8.6	2
Repo spread - LOIS						
3M	0.871(***)	0.286(***)	-0.236(***)	-0.005	3.3	4

Notes: b $|\theta|<1$. (*), (**), and (***) denotes significance at 10, 5, and 1%.

Table 5: VECM spreads with exogenous variables

08/09/2007 - 12/15/2008	**LOIS - TED**						**Repo spread - LOIS**	
	1M		**3m**		**6M**		**3M**	
	d(TED)	**d(LOIS)**	**d(TED)**	**d(LOIS)**	**d(TED)**	**d(LOIS)**	**d(Repo spread)**	**d(LOIS)**
d(fftr)	-0.15	0.10 *	-0.03	0.12 **	-0.02	0.06	-0.10	0.11 ***
taf auction date	-0.03	0.02	-0.06	0.03	-0.01	0.03	0.04	0.03
condition date	-0.01	-0.02	-0.01	-0.03	-0.06 *	-0.04 *	-0.01	-0.02
internat. news	0.01	0.03	-0.03	0.02	0.05	0.04	0.03	0.01
domestic news	-0.07	-0.08 *	0.03	-0.05	-0.05	-0.10 **	-0.05	-0.05

Notes: (*), (**), and (***) denotes significance at 10, 5, and 1% level. Results from macro news and calender effects are omitted.

Table 6: VECM: Exogenous variables

The findings of the models including the exogenous variables are outlined in Table 6. There is hardly any effect from augmenting the model exogenous variables. At this point, it is important to recall: First, the central bank can only affect the liquidity risk, while credit risk depends on the characteristics of the market participants. Second, the TAF measures did not change the overall liquidity provision since the actions were neutralized through open market operations until autumn 2008. Third, the limitations of the event study by using dummies to detect whether the TAF auctions were effective was discussed by other authors (i.e. Wu [2008], McAndrews et al. [2008]). The event windows are limited to one day. Given the amount of news during the turmoil it seems sensitive to keep this window as short as possible. Different to papers following Taylor and Williams [2009], the macro news releases are included to control for the fact that market participants not only pay attention to communication by policy makers but also to news about fundamentals.

In summary, according to these models, I find that there is a common trend to drive the Libor spreads. In line with theoretical assumptions, secured markets adjust to changes in the expected path of federal funds rate. In terms of the speed of adjustment to the new equilibrium, there is no difference in the liquidity among the different maturities. However, I find that flight to safety and/ or liquidity risk as incorporated in the difference between Tbill and OIS, Repo rate, respectively, only to have a short-run effects. However, given an eye inspection[17] as in Figure 2, it shows that the near zero target range in December 2008, changed the relationship between secured markets and hence the traditional interest rate channel completely. According to this framework, announcements of the Fed's liquidity programmes have hardly any affect on money market spreads dynamics of maturities up to 6 months.

[17] A Chow Test on the difference between 3months Tbill-OIS rate confirms this assumption.

03/03/2003 - 12/15/2008	LIBOR						CD rate						ED rate					
	1M		3M		6M		1M		3M		6M		1M		3M		6M	
ois	1.01	(***)	1.01	(***)	1.00	(***)	1.01	(***)	1.02	(***)	1.01	(***)	1.02	(***)	1.02	(***)	1.02	(***)
ffv	1.26	(***)	1.89	(***)	1.83	(***)	1.46	(***)	1.99	(***)	2.34	(***)	2.51	(***)	3.32	(***)	3.68	(***)
cds	0.53	(***)	0.71	(***)	0.90	(***)	0.68	(***)	1.01	(***)	0.97	(***)	0.71	(***)	0.97	(***)	1.15	(***)
constant	-0.03	(*)	-0.05	(***)	-0.06	(***)	-0.14	(***)	-0.19	(***)	-0.16	(***)	-0.18	(***)	-0.23	(***)	-0.27	(***)

Notes: Lag length according to the Schwarz criteria. Newey-West standard errors to compute the asymptotically valid standard errors for the coefficients. (*), (**), and (***) denote significance at 10, 5, and 1% level.

Table 7: Long-run relationship based on DOLS estimates

5.2 Transmission of monetary policy and money market volatility: 2003 to 2008

This model aims to estimate transmission of monetary policy, extending the model by Carpenter and Demiralp [2011]. Estimation results for long-run relationship as in Equation 7 and the error correction EGARCH model as in Equations 9 and 11 are summarised in Tables 7 and 8, respectively. Due to the results from cointegration testing, It seems reasonable to include the CDS median as an additional variable to the long-run relation. The realised federal funds volatility was not sufficient to restore the relationship between unsecured interbank rates and monetary policy at 6 months. On the other hand, including only the CDS median without the realised volatility, the residual based cointegration tests indicate a cointegration relationship[18]. However, the residuals of the models showed stronger mean-reverting behaviour including both CDS and realised volatility even at 3 months maturity. For models at one month maturity, the test regression of no cointegration can be rejected between interbank rate and the overnight swap but as for longer term rates, the cointegration relationship appears to be stronger including both risk measures. Carpenter and Demiralp [2011] find the realised federal funds volatility to be the missing link between monetary policy and interbank rates at 3 months maturity but they refer to a longer sample period. Turning to the regression outputs presented in Table 7, the most notable finding is the role of realised volatility on ED rates while the response of the Libor rate at different maturities terms is remarkably lower. The size of the impact on Libor dynamics resembles those of the CD rates. The CD market is an alternative funding source for financial institutions where banks can borrow from consumers. In previous literature (see for example Thornton [2009]) it was often argued that if the interbank market were liquidity constrained, the spread between Libor and CD rate would increase as the lenders would charge a higher risk premium on the Libor rate compared to the CD rate, which market is less liquidity constraint. Concerning the impact of the OIS rate, the findings are in line with the ones from Carpenter and Demiralp [2011]. However, unlike them, my estimated coefficients using dynamic OLS are super-consistent. On top of that, the findings also indicate that there is a one-to-one relationship between interbank funding costs and expected future federal funds rate from 1 up to 6 months.

[18] These test output are not documented to save space.

Table 8 outlines the findings from the error correction model[19]. One can see that the variables are cointegrated as all error correction terms are correctly signed and significant. The rates adjust to changes in monetary policy and risk measures. Rates at lower maturities adjust more strongly to restore the equilibrium relationship, in other words they are less liquidity constrained. Also, according to these outputs, overall the adjustments in the CD market are stronger than those in the Libor and ED market, implying that the CD market is more liquid. However, all of the adjustment coefficients appear to be rather small. Concerning the surprise component of a target rate change, the impact has changed after August 2007. Surprisingly, the effect on the interbank rates has increased during the crisis.[20] To control for the announcement effects, I estimated twice: first only including the auction dates of the TAF and secondly, I re-run the regression with a larger set of dummies by McAndrews et al. [2008][21]. The EGARCH turned out to be sensitive to the number of parameters. Some of the announcements lowered the mean of the rates. The effects are small. On the other hand, TAF announcements tend to have stabilised volatility of the Libor to greater extent. Also, there are signs of asymmetric responses to innovations in the ED and CDS rates at 3 and 6 months maturity. The model implies that since coefficient are negative, the response of the conditional variance to a positive shock at the previous period is lower than the response to a negative shock. Another finding is the increased volatility after a monetary policy surprise prior to the crisis for both Libor and ED rates, but during the crisis this increase is less pronounced. One possible explanation may be that the overall heightened volatility in the markets (see the positive signs of the shift dummies for the post-Lehman and the crisis period), dampened the effect of a target rate change. Former work by Nautz and Schmidt [2009] suggested that the introduction of interests paid on reserves, reduces overnight volatility. The effect on money markets volatility is less clear. Whereas the volatility of ED rates was stabilised, there is no sign that the interest paid on excess reserves calmed the Libor.

In summary, I find that monetary policy expectations in combination with credit and liquidity risk measures drive the unsecured interbank rates. Additionally, market liquidity, as measured by the speed of adjustment coefficients, appears to differ between the Libor and CD market. Overall, I find an immediate pass through measured by the unexpected target rate change on the mean, but hardly any effects from the TAF announcements during the crisis. On the money market volatility, however, the effects of target rate changes were less pronounced during the crisis than before. In contrast, on the TAF auction days, the Libor's volatility lowered.

[19] Again, findings from macro news or calendar effects are omitted to save space.

[20] Estimates of surprise component may be biased due to the fact that there was more than target rate change a month in January and October 2008.

[21] Carpenter et al. [2013] updated the set. The data is available on request.

03/03/2003 - 12/15/2008

LIBOR

	1M	1M	3M	3M	6M	6M
Mean Eq.						
lags (in diff.)	3	3	7	7	1	1
ECT	**-0.019*** **	**-0.019*** **	**-0.010*** **	**-0.016*** **	**-0.023*** **	**-0.026*** **
$fs*D^{crisis}$	0.59***	0.59***	0.75**	0.74***	0.79**	0.72*
fs	0.01	0.01	0.24**	0.17*	0.55***	0.48***
taf auction date	0.00	0.00	0.01*	0.0020	0.00	0.00
condition date	0.00		-0.01		0.00	
internat. news	0.00		0.00		0.01	
domestic news	-0.02		-0.09***		-0.04	
notification date	0.00		0.00		-0.01*	
Variance Eq.						
ω	-1.77***	-1.71***	-2.52***	-2.38***	-3.38***	-2.33***
$\lvert\varepsilon_{t-1}/\sigma_{t-1}\rvert$	0.77***	0.76***	0.96***	0.92***	0.52***	0.48***
$\varepsilon_{t-1}/\sigma_{t-1}$	0.09	0.08	0.07	0.04***	0.01	0.00
$\log(\sigma^2_{t-1})$	0.86***	0.87***	0.82***	0.83***	0.65***	0.77***
$\lvert fs\rvert*D^{crisis}$	-11.41*	-10.93	-16.12***	-17.05***	-7.29**	-5.37
$\lvert fs\rvert$	24.37***	23.54***	24.80***	24.17***	13.43***	10.88***
D^{FOMC}	-1.70**	-1.69**	0.71**	0.91***	0.47*	0.41
D^{crisis}	0.48***	0.47***	0.31***	0.29***	0.68***	0.46***
D^{postLB}	0.72***	0.61***	1.26***	1.10***	1.04***	0.72***
taf auction date	-2.51***	-2.72***	-1.35***	-1.40***	-2.50***	-1.32***
condition date	-0.12		0.06		1.40***	
internat. news	-0.08		0.10		0.14	
domestic news	-0.40		1.56***		0.11	
notification date	-0.20		-0.73**		-0.37	
D^{IOR}	-0.18	-0.13	-0.68*	-0.56*	-0.41	-0.34

CD rate[b]

	1M	1M	3M	3M	6M	6M
Mean Eq.						
lags (in diff.)	3	3	3	3	3	3
ECT	**-0.057*** **	**-0.038*** **	**-0.045*** **	**-0.046*** **	**-0.031*** **	**-0.035*** **
$fs*D^{crisis}$	0.12	0.14	0.34***	0.36***	0.92***	0.88***
fs	0.25	0.20	-0.10**	-0.09*	-0.37**	-0.35**
taf auction date	0.00	-0.01	-0.01	-0.03	0.01	-0.03
condition date	0.00		-0.05***		-0.04***	
internat. news	0.10***		-0.01		-0.02	
domestic news	-0.11***		0.00		-0.13***	
notification date	-0.03**		-0.01		-0.02	
Variance Eq.						
ω	-1.20***	-1.38***	-0.54***	-0.51	-0.21**	-0.25**
$\lvert\varepsilon_{t-1}/\sigma_{t-1}\rvert$	0.40***	0.42***	0.21***	0.20	0.08**	0.10***
$\varepsilon_{t-1}/\sigma_{t-1}$	-0.05	-0.09	-0.08***	-0.07**	-0.06***	-0.06***
$\log(\sigma^2_{t-1})$	0.89***	0.86***	0.95***	0.96***	0.98***	0.98***
$\lvert fs\rvert*D^{crisis}$	-1.83	-3.91	-4.04	-3.85***	-3.55	-3.38
$\lvert fs\rvert$	1.77	3.68	2.01	2.00	2.72	2.41
D^{FOMC}	-0.04	-0.11	0.43**	0.44***	-0.04	0.04
D^{crisis}	0.30**	0.36***	0.17***	0.17***	0.06**	0.07**
D^{postLB}	0.07	0.23	0.15*	0.22***	0.08	0.16***
taf auction date	-1.01	0.02	-0.65	-0.36***	0.25	-0.51***
condition date	1.53**		0.57*		-0.78*	
internat. news	0.08		0.25		0.14	
domestic news	0.75**		1.07***		1.03***	
notification date	-0.63*		-0.20		0.02	
D^{IOR}	0.26	0.12	-0.12	-0.18***	-0.04	-0.08

ED rate[b]

	1M	1M	3M	3M	6M	6M
Mean Eq.						
lags (in diff.)	3	3	2	3	3	3
ECT	**-0.024*** **	**-0.024*** **	**-0.026*** **	**-0.025*** **	**-0.022*** **	**-0.024*** **
$fs*D^{crisis}$	0.43***	0.41***	0.63*	0.73*	-0.22	-0.37***
fs	0.12	0.13	0.13	0.15	0.73**	0.83***
taf auction date	-0.01	0.00	-0.02**	-0.01	0.01	0.01***
condition date	0.00		0.02		0.00	
internat. news	0.05		0.01		0.00	
domestic news	-0.12***		-0.08***		-0.09***	
notification date	-0.01*		-0.01		-0.01	
Variance Eq.						
ω	-1.64***	-1.91***	-1.80***	-2.59***	-4.21***	-4.34***
$\lvert\varepsilon_{t-1}/\sigma_{t-1}\rvert$	0.31***	0.34***	0.31***	0.41***	0.40***	0.40***
$\varepsilon_{t-1}/\sigma_{t-1}$	-0.01	-0.02	-0.11**	-0.15***	-0.07	-0.07***
$\log(\sigma^2_{t-1})$	0.84***	0.81***	0.82***	0.73***	0.53***	0.52***
$\lvert fs\rvert*D^{crisis}$	-13.09**	-14.55***	-12.30***	-13.39***	-21.28***	-23.07***
$\lvert fs\rvert$	11.76**	12.98***	14.59***	16.08***	22.45***	23.59***
D^{FOMC}	0.02	0.02	0.32	0.30	0.93***	0.91***
D^{crisis}	0.65***	0.76***	0.53***	0.78***	1.22***	1.29***
D^{postLB}	0.52***	0.97***	0.74***	1.53***	1.88***	1.83***
taf auction date	-1.02	-1.58***	-1.18	-1.59***	-1.69***	-1.67***
condition date	-0.71		-0.50		0.03	
internat. news	2.16***		1.84***		-1.15*	
domestic news	0.07		1.33**		-0.62	
notification date	-0.40		-0.10		0.27	
D^{IOR}	0.13	-0.41*	-0.25	-0.87**	-0.87**	-0.82***

Notes: [b] For the CD and ED rates all Fed's actions are lagged by 1 day, since those rates are brokered prior to the FED's announcements but after the macro news.
Lag length in the Mean Eq. with SBC. Bollerslev-Woodridge robust standard errors and covariances. *, **, and *** denotes significance at 10, 5, and 1% level.

Table 8: Results EGARCH with error correction term

5.3 Dynamics of the interbank rates after a shock: 2007 to 2008

The volatility of the overnight market is typically mainly driven by financial institutions' liquidity concerns. In times of turmoil when markets are under pressure, uncertainty about the course of future monetary policy may occur. Heterogeneous views about of the central bank's policy intentions may have a significant impact on the movements in the overnight market. Whereas in the EGARCH framework I use realised volatility which is linked to the banks' liquidity management, this model includes a measure more closely related to uncertainty about the future path of monetary policy.

The aim of this model is to identify the dynamics of unsecured interbank rates after a shock without modeling long-run relationships between the variables between 2007 to 2008. Figures in the Appendix A.6 contain the impulse response functions of the interbank rates after a shock in the OIS rate, CDS and federal funds volatility. I chose that all measure to have a contemporaneous impact on the interbank rate[22]. I compared results from alternative orderings. Different ordering did not qualitatively change the results, especially in the case for the implied volatility. The magnitude of the shocks is small relative to the interest rates' own shocks not to blur responses from the other shocks. The most striking finding is the impact of an OIS shock on the Libor at different maturities. Compared to the other rates, the magnitude of the impulse is rather small at 3 and 6 months maturity. Not only have the monetary policy shocks had a small effect, but also the credit risk. At 3 months maturity, there is no immediate impact, only after 7 days. The effect, however, increases and over passes the impulse from the OIS rate after around two weeks. I also estimated a model with maturity of one week where the dynamics are completely different with hardly any impact from shocks in risk. For the CD rate and ED rate, on the other hand, the control of monetary policy is larger than for the Libor at the same maturities. The ED rates show some overshooting response to credit risk shocks after 2 to 3 days. Interestingly, the effect is larger, the shorter the maturity of the rate. The effect decreases after a week and co-moves with the response shock in monetary policy expectations. Overall, hardly any positive reaction follows after a liquidity shock proxied by the federal funds volatility and if only at 1 month maturity of the ED rate. The reaction turns out to be even negative. For further robustness, I also applied generalised impulse response functions as an identification technique. However, findings did not fundamentally change. Tables in the Appendix A.7 display the variance decomposition of each of the spreads on the first, fifth, tenth, 15th and 20th day after a shock. Again, as in the impulse response functions, the rates account for the major part of its own variability. Especially, in the case of the Libor at 3 and 6 months other shocks only account for around 8 to 11 percent of the Libor's volatility after 20 days, while other shocks account for 30 to 50 percent. The variability primarily attributes to the credit risk shocks and monetary policy shocks. Appendix A.5 presents the findings from the GC testing. For comparison, I also present GC testing for VARs including 3 months GC repo and Tbill rate as well as the variance decomposition of the models. One can observe the different dynamics in comparison to unsecured interbank rates.

In summary, I find hardly any evidence that shocks in the federal funds IV affected interbank rates. CD and ED rates show stronger adjustment after a shock in monetary policy expectations,

[22] Cholesky ordering: CDS - OIS - ffiv - interbank rate.

than the Libor rate.

6 Conclusion

The money markets play a crucial role in the transmission of monetary policy. The Fed controls the amount of bank reserves and therefore that the federal funds rate stays close to the target rate. Via the expectation of future target rate changes, the central bank is albe to influence longer-term rates. The 3 months Libor, a rate in the unsecured money market, has become the benchmark for pricing a large number of various financial contracts and thereby affecting the entire economy. This mechanism is called the interest rate channel. Pre-crisis literature studies the link between money market rates and finds that expectations over monetary policy drive the interest rates in the long-run. The turmoil of the financial crisis deeply distorted this channel and turned attention to the functioning of the interbank markets.

The objective of this paper is to extend crisis and pre-crisis literature of the interest rate channel and to analyse the long and short-term links between money market rates and monetary policy in an environment of heightened uncertainty. By the end of 2008, when reserve levels increased and hence the overnight rates fell near zero, the U.S. central bank employed other operational targets than the federal funds rate. I therefore limit my sample to December 2008. I estimate three different empirical models to evaluate the interest rate channel.

First, using a VECM model, I find that Libor spreads move together during the financial crisis due to the link between monetary policy expectations and secured rates. Moreover, I find them to adjust to expectations about future monetary policy target rate changes over the same term as indicated by theoretical assumptions. Second, similar to pre-crisis pass-through models, I investigate the interest rate channel to unsecured interbank rates. I employ a dynamic OLS model for the long-run relationship and further an EGARCH framework with an error correction term. Considering the pass-through to the unsecured interbank rates, I find that the relationship deteriorated since rates are subject to additional drivers such as credit and liquidity risk. In addition, although sharing a similar exposure to counterparty risk, the CD market is more liquid than the ED and Libor markets. The finding of the CD market may contribute to the growing theoretical papers that study the channels by which shocks can lead to evaporation of market liquidity. Also, I find that announcement effects of the liquidity programmes tended to stabilise the money market volatility. The third empirical model, a simple VAR, investigates the dynamics of interbank rates after a shock. Findings indicate that interbank rates respond to innovations in credit risk and monetary policy. Given the findings from the models, I conclude that unsecured interbank markets disconnected from monetary policy expectations and are now subject to additional long-run trends. On the other hand, secured money market instruments such as Treasury bills or the general collateral repurchase agreements, still co-moved and also adjusted to changes in monetary policy expectations. They only diverged in the short-run. The increasing amounts of reserves and overnight rates near zero, however, marked the beginning of a new policy framework with a change in the operational target. After all, one has to acknowledge the fact that all term markets were deeply disrupted. Interbank funding concentrated on very short-term loans, mostly overnight. This raises the question about the reliability of the findings in studies covering longer term money market rates. Nevertheless, in the light of the discussion about an adequate "exit strategy" from the current environment with high liquidity in the banking system, one has to re-evaluate the traditional interest rate channel and possibly also the choice of the reference rate.

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A Appendix

A.1 Variables

	Name	Description	Literature	Source
libor	Libor	London interbank offered rate at 1 week, 1, 3, and 6 months maturity. Collected around 11 a.m. London time. Adjusted for one day according to previous literature.	Taylor and Williams, 2008	Bloomberg
cd	CD rate	Certificate of deposit rate at 1, 3, and 6 months maturity. Collected around 8 to 9.45 am NY time.	Sarno and Thornton, 2003; Taylor and Williams, 2008; Thornton, 2009	Bloomberg
ed	ED rate	Eurodollar deposit rate at 1, 3, and 6 months maturity. Collected around 9.30 am NY time.	Taylor and Williams, 2008; Zhou, 2007; Colarossi and Zaghini, 2009	Bloomberg
ois	OIS rate	Overnight index swap at 1week and 1, 3, and 6 months maturity.	Taylor and Williams, 2008	Bloomberg
tbill	Tbill rate	Treasury bill rate, secondary market at 1, 3 and 6 months maturity.	Sarno and Thornton, 2003; Ehrmann and Fratzscher, 2007	Bloomberg
repo	GC Repo rate	General collateral repurchase agreements at 3 months maturity.	Hoerdahl and King, 2008	Bloomberg
lois	LOIS spread	Libor-OIS spread		
ted	TED spread	Libor-Tbill spread		
tep	Repo spread	Libor-GC repo spread		
cds	CDS median	Median of credit default swaps, 5 years maturity, from the banks: BOFA , BOTM, BACR , CINC, CRDSUI, DB , HSBC BK, JPMCC, LLOY, RABOBK, NORBK, RBOS, UBS	i.a. Taylor and Williams, 2008	Bloomberg
fftr	Target rate	Federal funds target rate		FRED
ffv	Realised FF volatility	Absolute average deviation from the target rate over the last 30 days.	Hilton, 2005; Carpenter and Demiralp, 2011	FRED
ffiv	Implied vola FF futures options	Log of implied volatility from Federal funds futures (2nd Nearby) options. Average of put and call options IV.	Neely, 2004	Bloomberg
news	Macro news	Announcements of macro news such as: Consumer confidence, retail sales, production and unemployment. Surprise component is extracted by deducting the median from the Bloomberg survey and standardised by dividing it through its standard deviation.	Andersen et al. 2002; Ehrmann and Fratzscher, 2007; Moessner and Nelson, 2008	Bloomberg
fs	MP surprise	Suprise component of a target rate change extracted from the Federal funds futures rate (1st Nearby).	Kuttner, 2001	Bloomberg
D^{TAF}	TAF effects	Term auctions facility announcements as: Auction date, condition date, international and domestic news, and notification date. For a description refer to McAndrews et al. 2009. Each series accounts for 1 at the announcement date, and 0 otherwise.	McAndrews et al. 2009; Carpenter et al., 2013	Bloomberg/ Literature
D^{FOMC}	FOMC	Accounts for 1 on the days the Federal Open Market Committee takes place and 0 otherwise.	Ehrmann and Fratzscher, 2007; Nautz and Schmidt, 2009	Bloomberg
D^{IOR}	IOR Dummy	Shift dummy for the time when the Fed started paying interest on reserves: 1 from Oct 9, 2008 and 0 before.	Nautz and Schmidt, 2009	-
D^{crisis}	Crisis Dummy	Shift dummy that includes 1 from Aug 9, 2007 and 0 before.	-	-
D^{postLB}	Post-Lehman Dummy	Shift dummy that includes 1 from Sept 15, 2008 and 0 before.	-	-
X	Calender effects	3 vectors for the last business day of the month, quarter and year denoting 1 at those days, 0 otherwise.	i.a. Hamilton, 1996	-
X	Events	Aug 9, 2007, March 14, and Sept 15, 2008 denotes 1, 0 otherwise.	-	-

Table 9: List of variables

A.2 Unit root and stationarity tests

Before starting with the empirical analysis, I first determined the order of integration of the variables using various testing techniques: (i) Augmented Dickey Fuller (ADF), (ii) Philips-Perron (PP), (iii) Kwiatowski-Phillips-Schmid-Shin (KPSS) and (iiii) Elliott-Rothenberg-Stock (ERS) test.

The following two test regression are considered for the ADF in case of interest rates and risk measures. From an economic perspective, it is not obvious to include a drift term for an interest rate over a longer period of time. However, to be in line with previous literature, I test both: H0 of random walk with 14 and without drift 13 against the alternative hypothesis of an autoregressive process with nonzero mean, and zero mean, respectively. The spreads, on the other hand, are only tested with the first test regression without a drift term in the regression.

$$\Delta y_t = \alpha_0 y_{t-1} + \sum_{i=1}^{p} \beta_i \Delta y_{t-i} + \epsilon_t \tag{13}$$

$$\Delta y_t = c + \alpha_0 y_{t-1} + \sum_{i=1}^{p} \beta_i \Delta y_{t-i} + \epsilon_t \tag{14}$$

One can reject H0 of a unit root if $\alpha_0<0$. The null and alternative hypothesis are the same for both, ADF and PP test. The only difference is that the ADF test extends the model with extra parameters accounting for serial correlation among the innovations. In the case of stationary series but with strong autocorrelation, ADF and PP tends not to reject the H0 of a unit root. This problem especially occurs in the case of small sample sizes. Therefore I also test for stationarity using the KPSS method which is the inverse of the PP test. I run the following regression:

$$y_t = x_t + e_t \tag{15}$$

$$x_t = x_{t-1} + v_t \tag{16}$$

With e_t being a stationary process and y_t is regressed on an exogenous variable called x_t which is a random walk with v_t being an i.i.d. process with a zero-mean and a variance of σ^2. Under the H0 σ^2=0. The alternative hypothesis is $\sigma^2>$ 0, which means that the random walk contains a unit root. Alternatively, I also applied another unit root test with stronger power in small sample sizes, the ERS test. The ERS is similar to the ADF, but with generalised least square detrending.

To ensure that the variables can be treated as I(1) processes, I re-run the regressions on the first differences of the variables. Please note that these test regressions for the first differences do not include a c in the case of ADF and PP.

The 10 provides an overview of the variables at various sample periods tested.

		LIBOR				OIS				ED			CD			TBILL			REPO	*ffv*	*ffiv*	*cds*
		1week	**1M**	**3M**	**6M**	**1week**	**1M**	**3M**	**6M**	**1M**	**3M**	**6M**	**1M**	**3M**	**6M**	**1M**	**3M**	**6M**	**3M**			
03/03/2003 -08/09/2007 (pre-crisis)																						
ADF	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	-	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	-	I(0)
PP	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	-	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	-	I(0)
ERS	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	-	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	-	I(0)
KPSS	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	-	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	-	I(0)
03/03/2003 -12/15/2008 (including crisis)																						
ADF	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	-	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	-	I(0)
PP	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	-	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	-	I(0)
ERS	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	-	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	-	I(0)
KPSS	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	-	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	-	I(0)
08/09/2007 -12/15/2008 (crisis)																						
ADF	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)
PP	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)
ERS	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)
KPSS	*level*	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**	**I(1)**
	difference	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)	I(0)

Table 10: Summary of UR and stationarity testing

A.3 Single regression cointegration tests

All variables can be treated as I(1) processes, hence it is sensible to test for common stochastic trends since in the case of cointegration, simple differencing is a model misspecification as long-term information appear in levels.. The concept of cointegration implies that there is a long-run equilibrium with nonstationary variables. Those variables, however, embed a stationary linear combination of variables. Equilibrium relationship indicates that there is no deviation in the long-run, however, variables may diverge from the equilibrium in the short run [Enders, 2010, p. 356-365]. Tests conducted in this paper are single regression tests by (i) Engle Granger (EG) and (ii) Phillips Ouliaris (PO).

The EG two-step methodology is a unit root test on the residuals of the test regression 17. Since residuals are estimated, one needs to apply different critical values than for the ADF.

$$y_t = c + \beta_1 x_t + \upsilon_t \tag{17}$$

Recall that the EG approach can only identify a single cointegrating relationship. PO also tests the non stationarity of the υ_t.

The results from single regression cointegrating testing are summarised in Tables 11 to 13.

	TED - LOIS			**REPO spread - LOIS**
	1M	**3M**	**6M**	**3M**
08/09/2007 - 12/15/2008				
EngleGranger	cointegrated (***)	cointegrated (**)	cointegrated (**)	cointegrated (**)
Phillips Ouliaris	cointegrated (***)	cointegrated (**)	cointegrated (**)	cointegrated (***)

Notes: Lag length determined with SIC. (*), (**), (***) denotes significance at 10, 5, and 1%.
Test regressions include a constant term.

Table 11: Single cointegration regression testing for the spreads

	Libor & OIS			CD & OIS			ED & OIS		
	1M	3M	6M	1M	3M	6M	1M	3M	6M
03/03/2003 - 08/09/2007 (pre-crisis)									
EngleGranger	cointegrated (***)	cointegrated (*)	cointegrated (**)	cointegrated (***)	cointegrated (**)	cointegrated (**)	cointegrated (***)	cointegrated (**)	cointegrated (**)
Phillips Ouliaris	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (**)	cointegrated (**)	cointegrated (***)	cointegrated (**)	cointegrated (**)

	Libor & OIS			CD & OIS			ED & OIS		
	1M	3M	6M	1M	3M	6M	1M	3M	6M
03/03/2003 - 12/15/2008 (incl. crisis)									
EngleGranger	cointegrated(**)	*not cointegrated*	*not cointegrated*	cointegrated (*)	*not cointegrated*	*not cointegrated*	cointegrated (***)	*not cointegrated*	*not cointegrated*
Phillips Ouliaris	cointegrated(**)	*not cointegrated*	*not cointegrated*	cointegrated (***)	*not cointegrated*	*not cointegrated*	cointegrated (**)	*not cointegrated*	*not cointegrated*

Notes: Lag length determined with SIC. (*), (**), (***) denotes significance at 10, 5, and 1% level.
Test regressions include a constant term.

Table 12: Single cointegration regression testing for the unsecured interbank rates w/o RP

	Libor & OIS & ffv			CD & OIS & ffv			ED & OIS & ffv		
	1M	3M	6M	1M	3M	6M	1M	3M	6M
03/03/2003 - 12/15/2008 (incl. crisis)									
EngleGranger	cointegrated (**)	cointegrated (***)	*not cointegrated*	cointegrated (***)	cointegrated (*)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (*)
Phillips Ouliaris	cointegrated (**)	cointegrated (*)	*not cointegrated*	cointegrated (***)	cointegrated (***)	cointegrated (**)	cointegrated (***)	cointegrated (**)	*not cointegrated*

	Libor & OIS & ffv & cds			CD & OIS & ffv & cds			ED & OIS & ffv & cds		
	1M	3M	6M	1M	3M	6M	1M	3M	6M
03/03/2003 - 12/15/2008 (incl. crisis)									
EngleGranger	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (*)
Phillips Ouliaris	cointegrated (**)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)	cointegrated (***)

Notes: Lag length determined with SIC. (*), (**), (***) denotes significance at 10, 5, and 1% level.
Test regressions include a constant term.

Table 13: Single cointegration regression testing for the unsecured interbank rates w/ RP

A.4 Johansen methodology

Different to EG and PO whose regressions are estimated with OLS, maximum likelihood is applied, avoiding conditional estimates. The Johansen procedure relies on the relationship between rank "'r"' of a matrix Π and it characteristic roots. It is a multivariate generalisation of the Dickey-Fuller test [Enders, 2010, pp. 385-387].

$$\Delta Y_t = \Pi Y_{t-1} + \sum_{k=1}^{n-1} \Gamma_k \Delta Y_{t-k} + \epsilon_t \tag{18}$$

Note that the VECM on the single interest rates is augmented with a drift term during.

$$\Delta Y_t = c + \Pi Y_{t-1} + \sum_{k=1}^{n-1} \Gamma_k \Delta Y_{t-k} + \epsilon_t \tag{19}$$

The results from the Johansen maximum likelihood cointegration procedure for the bivariate VECM are summarised in Table 14. The test results for the H0 of r$\leq$1 and r=1 for the Trace and Maximum eigenvalue, respectively are omitted. However, in all cases the H0 cannot be rejected at 5 per cent.

		Maximal eigenvalue statistics	**Trace eigenvalue statistics**
		P-value for H0 of no cointegration r=0; against H1 of r=1	P-value for H0 of no cointegration r=0; against H1 of r>0
08/09/2007 - 12/15/2008			
TED - LOIS			
	1M	0.04	0.03
	3M	0.05	0.04
	6M	0.02	0.04
Repo spread - LOIS			
	3M	0.00	0.00
Tbill - OIS[a]	**1M**	0.00	0.00
	3M	0.01	0.01
	6M	0.05	0.04
Repo - OIS[a]	**3M**	0.00	0.00

Notes: [a] LR tests suggest a drift in the VAR in differences.

Table 14: Johansen test for the spreads

A.5 Granger causality tests

			dependant variable			
		df	***interbank rate***	***ois***	***cds***	***ffiv***
08/09/2007 - 12/15/2008						
LIBOR	**1week**	**9**	ois(***) cds(***) ffiv ALL(***)	libor cds ffiv ALL	libor (**) ois ffiv ALL (**)	libor ois (***) cds (**) ALL (***)
	1M	**3**	ois cds ffiv ALL	libor (***) cds ffiv ALL (***)	libor (**) ois ffiv ALL (**)	libor ois cds (**) ALL (***)
	3M	**10**	ois (*) cds (*) ffiv ALL	libor (***) cds (*) ffiv (**) ALL (***)	libor ois ffiv ALL	libor ois cds (**) ALL (***)
	6M	**11**	ois cds ffiv ALL	libor (***) cds ffiv ALL (***)	libor ois ffiv ALL	libor (**) ois cds ALL (***)
CD	**1M**	**3**	ois (***) cds (***) ffiv ALL (***)	cd cds ffiv ALL	cd (**) ois (**) ffiv ALL (**)	cd ois cds (**) ALL (***)
	3M	**3**	ois (***) cds (***) ffiv ALL (***)	cd cds ffiv ALL	cd (*) ois (***) ffiv ALL (***)	cd ois (*) cds (**) ALL (***)
	6M	**8**	ois (***) cds (***) ffiv ALL (***)	cd cds ffiv ALL	cd ois ffiv ALL	cd ois (*) cds ALL (*)
ED	**1M**	**7**	ois (***) cds (***) ffiv ALL (***)	ed (***) cds ffiv ALL (***)	ed (***) ois ffiv ALL (**)	ed ois (*) cds (**) ALL (**)
	3M	**8**	ois (***) cds (***) ffiv ALL (***)	ed (**) cds ffiv ALL (***)	ed ois ffiv ALL	ed ois cds (**) ALL (***)
	6M	**6**	ois (***) cds (***) ffiv ALL (***)	ed cds ffiv ALL (*)	ed ois (**) ffiv ALL (*)	ed ois cds (**) ALL (**)
REPO	**3M**	**8**	ois (***) cds (***) ffiv (***) ALL (***)	repo (**) cds ffiv (**) ALL (***)	repo (**) ois (**) ffiv ALL (**)	repo ois cds (*) ALL (*)
TBILL	**3M**	**7**	ois (**) cds (***) ffiv ALL (***)	tbill (***) cds ffiv ALL (***)	tbill ois ffiv ALL	tbill ois cds (**) ALL (***)

Notes: According to Toda and Yamamoto, 1995. (*), (**), and (***) denotes significance at 10, 5, and 1% level.

Table 15: Granger causality tests for VAR

A.6 Impulse response functions

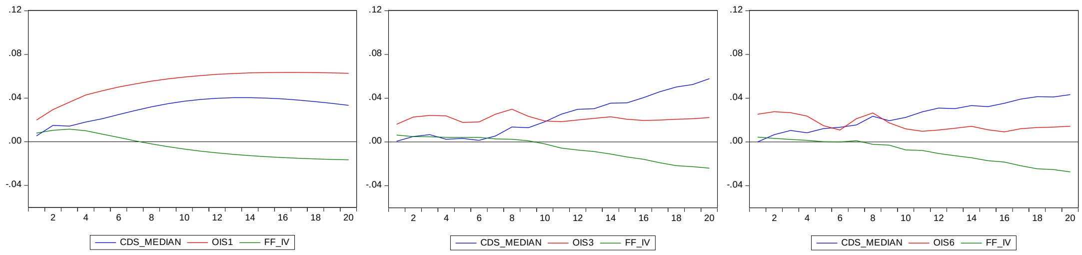

Table 16: Responses of Libor of 1, 3 and 6 months

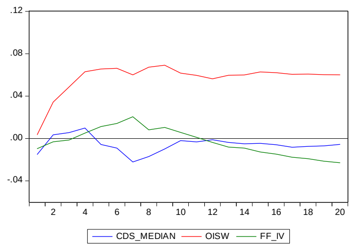

Table 17: Responses of 1week Libor

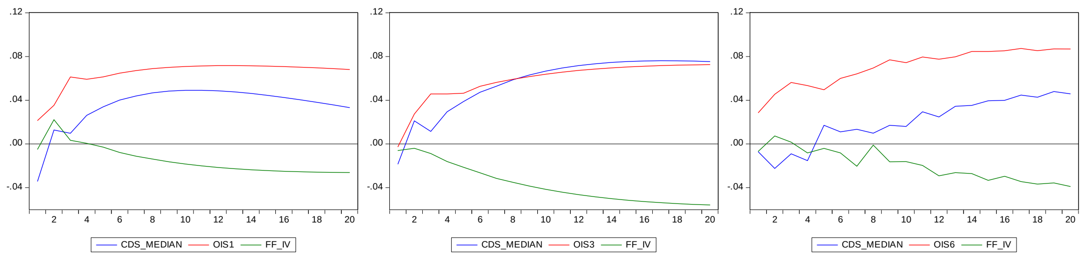

Table 18: Responses of CD rate of 1, 3 and 6 months

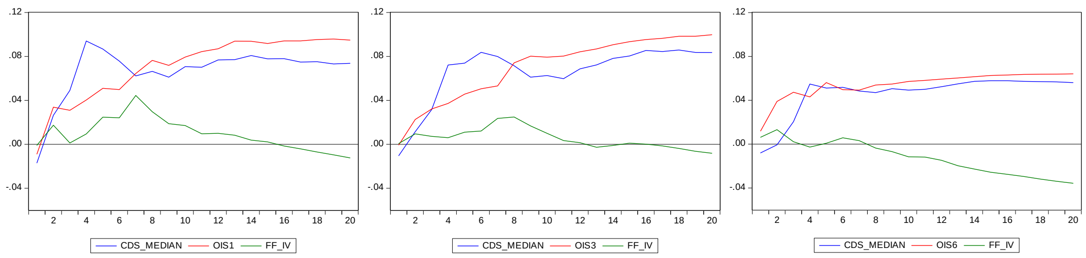

Table 19: Responses of ED rate of 1, 3 and 6 months

A.7 Variance decomposition

LIBOR

08/09/2007 - 12/15/2008

horizon	1 week *cds*	1 week *ois*	1 week *ffiv*	1M *cds*	1M *ois*	1M *ffiv*	3M *cds*	3M *ois*	3M *ffiv*	6M *cds*	6M *ois*	6M *ffiv*
1	2.09	0.12	0.84	0.57	7.56	1.19	0.03	10.17	1.48	0.00	15.81	0.48
5	0.42	12.59	0.27	1.98	10.60	0.73	0.30	7.75	0.41	1.33	10.34	0.14
10	0.68	16.63	0.55	4.27	14.84	0.37	0.83	5.11	0.16	2.80	5.79	0.13
15	0.47	16.81	0.47	6.48	18.75	0.55	2.67	3.33	0.29	4.57	3.46	0.61
20	0.41	17.13	0.81	7.60	22.25	0.88	4.88	2.52	0.75	6.34	2.57	1.57

Notes: Choleski ordering: cds - ois - ffiv - libor

Table 20: Variance decomposition LIBOR models

CD rate

08/09/2007 - 12/15/2008

horizon	1M *cds*	1M *ois*	1M *ffiv*	3M *cds*	3M *ois*	3M *ffiv*	6M *cds*	6M *ois*	6M *ffiv*
1	2.21	0.88	0.04	0.86	0.02	0.09	0.26	4.06	0.22
5	2.33	9.10	0.38	2.91	6.27	0.74	1.50	14.70	0.24
10	5.89	15.49	0.65	8.76	10.61	3.02	1.21	20.35	0.69
15	8.13	20.16	1.32	12.98	13.26	5.14	2.77	24.96	1.81
20	9.96	23.91	2.04	15.43	15.04	6.80	4.67	28.34	2.99

ED rate

horizon	1M *cds*	1M *ois*	1M *ffiv*	3M *cds*	3M *ois*	3M *ffiv*	6M *cds*	6M *ois*	6M *ffiv*
1	0.78	0.21	0.00	0.97	0.00	0.01	0.68	1.54	0.42
5	11.44	3.71	0.58	13.30	5.62	0.34	8.68	12.68	0.32
10	11.76	8.41	1.41	1.05	21.22	22.25	10.28	12.90	0.26
15	13.33	13.19	1.00	18.30	19.01	0.58	11.39	14.15	0.82
20	14.52	16.85	0.83	20.36	23.30	0.44	12.44	15.47	1.88

horizon	REPO rate 3M *cds*	REPO rate 3M *ois*	REPO rate 3M *ffiv*	TBILL 3M *cds*	TBILL 3M *ois*	TBILL 3M *ffiv*
1	3.02	3.81	0.28	6.07	15.78	0.12
5	10.79	26.50	1.26	20.54	24.76	0.57
10	11.15	47.19	3.29	27.38	31.85	0.72
15	15.24	53.45	2.56	34.39	33.40	0.70
20	17.68	56.08	2.12	38.05	33.85	1.04

Notes: Choleski ordering: cds - ois - ffiv - money market rate

Table 21: Variance decomposition VAR models